Instrument Tracking and Visualization for Ultrasound Catheter Guided Procedures

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Laura J. Brattain[1,2], Paul M. Loschak[1], Cory M. Tschabrunn[3], Elad Anter[3], and Robert D. Howe[1]

[1] Harvard School of Engineering and Applied Sciences, Cambridge, MA USA
[2] MIT Lincoln Laboratory, Lexington, MA USA
[3] Harvard-Thorndike Electrophysiology Institute, Beth Israel Deaconess Medical Center, Harvard Medical School, Boston, MA USA

Abstract. We present an instrument tracking and visualization system for intra-cardiac ultrasound catheter guided procedures, enabled through the robotic control of ultrasound catheters. Our system allows for rapid acquisition of 2D ultrasound images and accurate reconstruction and visualization of a 3D volume. The reconstructed volume addresses the limited field of view, an inherent problem of ultrasound imaging, and serves as a navigation map for procedure guidance. Our robotic system can track a moving instrument by continuously adjusting the imaging plane and visualizing the instrument tip. The overall instrument tracking accuracy is 2.2mm RMS in position and 0.8° in angle.

Keywords: instrument tracking, intra-cardiac imaging, volume rendering, procedure guidance

1 Introduction

Catheters enable many diagnostic and repair procedures to be accomplished with minimal collateral damage to the patients healthy tissues. In complex catheter procedures, workflow is often limited by visualization capabilities, which contributes to operator's inability to prevent and assess complications, as well as facilitation of key procedural components. In electrophysiological (EP) cardiac procedures, guidance is largely provided by fluoroscopy. However this imaging modality is unable to image soft tissues. To compensate for this shortcoming, a widely adopted approach is to generate a 3D electrophysiological model resembling the shape of the cardiac chamber by using a magnetic position sensing system that records the locations of the ablation catheter tip in space. The point clouds of the catheter tip positions may then be registered to a CT or MRI based pre-operative anatomical model and displayed to the clinician with the real-time positions of the catheters superimposed [1, 2]. Although the acquisition of catheter based geometry is acquired in real-time, the registration with pre-operative rendered anatomy is not, and thus may result in an anatomic mismatch at the time of the procedure.

Ultrasound (US) imaging catheters (intra-cardiac echocardiography, or ICE) have been routinely used in EP procedures for over a decade [3]. These catheters are inserted into the patients vasculature (e.g. femoral vein) and navigated to the heart, where they acquire B-mode images of cardiac structures. Compared to external probes, ICE can achieve higher quality views of targets in the near field with higher acoustic frequencies, reducing aberration and attenuation. The versatility of ICE imaging is particularly important during EP procedures, as it provides excellent visualization of all cardiac chambers when the probe is placed in the appropriate anatomic position. Recent studies suggest that ICE monitoring of lesion formation may increase the effectiveness of ablation procedure [3, 4].

Unfortunately, controlling ICE catheters requires the clinician to aim the imaging plane by manually turning control knobs and rotating and advancing the catheter handle. This makes it highly challenging to align the image plane with the target, thus moving between targets requires extensive time and skill to obtain an adequate view. During navigation of a working catheter based instrument, cardiologists presently use a combination of pre-operative images, fluoroscopic imaging, electroanatomic mapping, and minimal haptic feedback through the catheter handle. However, the actual instrument tip-to-tissue interaction can only be visualized in real-time with the use of US imaging, and these interactions could be effectively visualized with ICE. This presents a challenge for the operator because significant training and time are required to manually maneuver the ICE catheter. As a result, the use of ICE has largely been limited to a few critical tasks such as transseptal puncture.

We hypothesize that automatic tracking of the working instrument tool tip with direct visual feedback will better facilitate cardiac procedures such as ablation, including confirmation of adequate instrument tip-to-tissue contact. Real-time monitoring also enables rapid lesion assessment and may aid in the detection of impending complications. Automatic panoramic US imaging and enhanced displays also promise to decrease the need for fluoroscopy, reducing ionizing radiation exposure to patients and medical personnel. To our knowledge, no similar capability has been reported in the literature. Instrument tracking and real-time visual feedback using ICE are unique contributions of our system.

In this paper, we begin with an overview of the hardware of a robotic ICE steering system, which we previously developed. Next, we describe the imaging capabilities that we have developed for 3D mosaicing and instrument tracking, followed by experimental results. We conclude with a discussion of both the contributions and limitations of our current system.

2 System and Design

2.1 System Overview

We developed a robotic ICE control system to automate the pointing of ICE catheters. An ICE catheter, such as the one shown in Fig. 1, is a four degree-of-freedom (DOF) system that has two orthogonal bending directions and can translate along and rotate about its base axis. Our robotic manipulator has four motors, each controlling one of the four DOFs (Fig. 2). We derived and implemented a closed-form solution for forward and inverse catheter kinematics, which controls ICE tip position and imaging plane orientation [5]. An electromagnetic (EM) tracker system (trakSTAR, Ascension Technology, Shelburne, VT, USA) is used for closed loop control, performance validation, and safety functions.

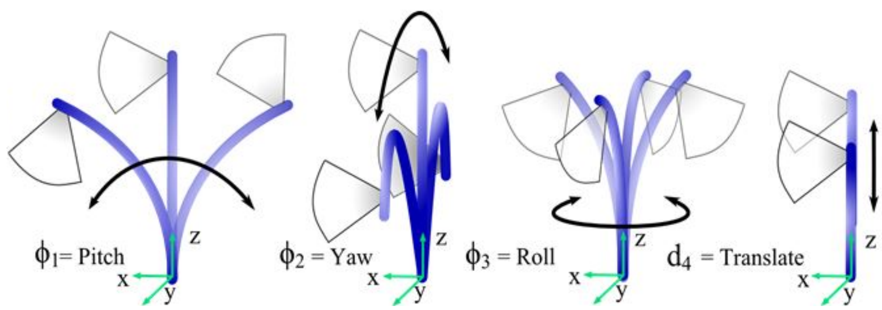

Fig. 1. A schematic diagram showing the four degrees of freedom of an ICE catheter.

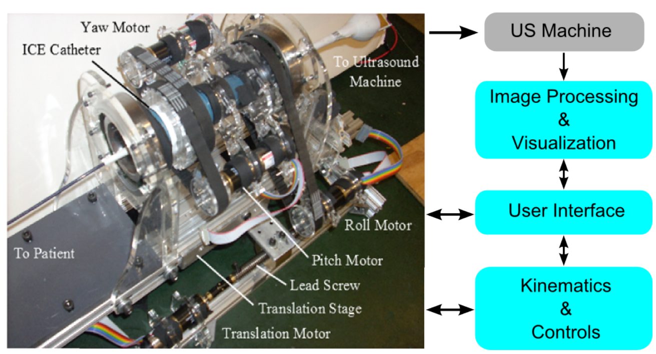

Fig. 2. System Overview. (*Left*) Robotic manipulator. (*Right*) System key modules and workflow.

2.2 System Capabilities

Safety is always a priority in a clinical environment, thus being able to perform imaging tasks while keeping the ICE catheter tip stationary is a useful capability. Based on this important assumption, we developed the following key capabilities:

Sweeping: Automated image plane sweeping adjusts the imager while keeping the ICE catheter tip at a fixed location to build a real-time 3D 'panorama'

(Fig. 3(a)). This shows the tissue structure across a treatment area and beneath the surface. The sweeping capability is different from simply rotating the catheter handle or body around its rotational axis in that it actually uses a combination of three knob adjustments to rotate the imager about its distal tip. During manual manipulation, a clinician may wish to position the ICE catheter in a desired region of the heart and sweep the imaging plane to get a comprehensive view of the region. When the catheter tip is already in a bent configuration, it is extremely difficult to intuitively spin the catheter manually about its own axis while keeping the tip in place. In automated sweeping, the user may input the desired range of angles to sweep with a specified angular resolution. By combining position and roll control, the US transducer can be rotated to a desired angle while the tip is continuously position controlled to remain at a fixed point. Several sweeps can be done at a few different user specified locations to generate a large, patient specific anatomical map for real-time navigation guidance.

Instrument Tracking: In instrument tracking mode, the system can follow the tip of an instrument (e.g. ablation catheter). The robot aims the imaging plane at a moving target while keeping the ICE catheter tip at a fixed and safe location (Fig. 3(b)). This is achieved by computing the angle between the target and the ICE imaging plane and commanding a specific roll. The position controller makes small adjustments of the ICE catheter tip position during the roll to maintain the stationary position.

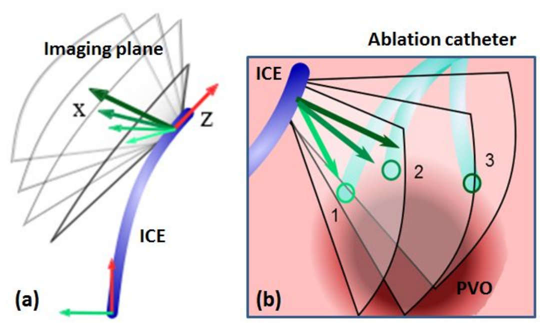

Fig. 3. Schematic illustration of system capabilities. (a) Sweeping. (b) Tracking ablation catheter tool tip.

2.3 3D Reconstruction of 2D ICE Images From Sweeping

The sweeping functionality enables the acquisition of closely spaced 2D images across a user specified region of interest (ROI). The 2D slices are non-parallel sections which need to be spatially registered to a common Cartesian coordinate frame using the tool tip positions acquired by the EM tracker and then interpolated and compounded into a gridded 3D volume. Fig. 4 shows the 3D panorama creation pipeline. There are several leading methods for 3D reconstruction of ultrasound images [6–10]. Our method is essentially the voxel-based interpolation. In order to achieve real-time performance, we implemented the 3D stitching and visualization on a GPU based on our previous real-time mosaicing technique for 3D/4D ultrasound [11, 12].

The registered 2D slices typically are not well aligned with the gridded space, resulting in gaps in the reconstructed 3D volume. Fortunately, the 2D slices can be acquired at any spacing, so the gaps can be made small, at the expense of longer sweeping times. Furthermore, the actual catheter tip locations at two adjacent frames and the commanded tip trajectory are known. This allows us to generate an image through a 'virtual' tip position on the trajectory by projecting images from the two closest 2D frames to the virtual position. The new image is then interpolated onto the 3D volume. Coupe [13] reported a similar 3D freehand US reconstruction method using probe trajectory (PT), and concluded that since the virtual slice was generated by using the information from the closest two frames, this method outperformed traditional approaches such as Voxel Nearest Neighbor (VNN) [14] and Distance Weighted interpolation (DW) [15]. The main limitation of the PT method was the assumption of constant probe speed between two slices. This limitation does not exist in our system because the actual tip location and commanded trajectory are known.

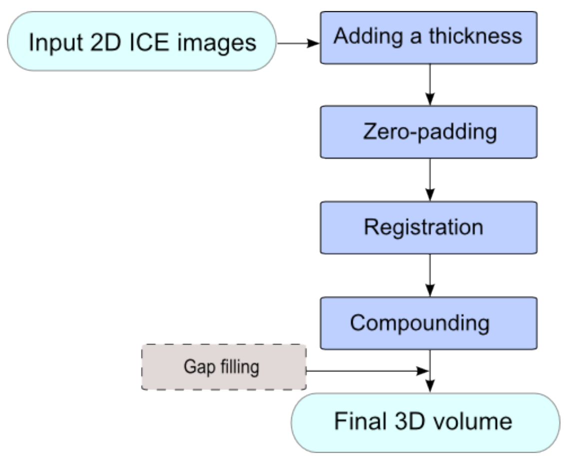

Fig. 4. 3D Panorama creation pipeline.

3 Experimental results

3.1 Sweeping

We conducted water tank experiments using gelatin-based phantoms that closely mimic the geometric and echogenic properties of animal tissue. The ICE catheter was connected to a Siemens Acuson X300 US imaging system and introduced through the side of the water tank where the imaging phantom was located.

The first experiment was to sweep across a specified ROI and build a 3D panorama. The imaging phantom was shaped to resemble the left atrium with four openings that simulate the pulmonary vein ostia (PVO), which are the critical areas for imaging during an atrial fibrillation ablation procedure. The atrium area (the opening in the phantom) was roughly $40m \times 40mm$. The ICE tip was directly in front of the phantom (Fig. 5(a)). The images were acquired at $90mm$ depth and $6.7MHz$ frequency. The system swept across the phantom in $1°$ increments over $40°$ while the ICE tip position remained stationary. Volume rendering was done as described in Sec. 2.3. Fig. 5(b)-(d) shows the reconstructed volume in three views. The PVOs are easily seen from Fig. 5(c).

To compute the reconstruction accuracy, features along the sweeping trajectory were measured and compared to their actual dimensions. Phantom atrium width and the length of two PVO vessels were manually determined in QLAB (Philips Healthcare, Andover, MA) in 20 images. Corresponding physical ground truth values were obtained by caliper measurements ($\pm 0.25mm$). Analysis shows that system accuracy is $0.96mm$ RMS (range $0.68 - 1.3mm$).

To register and interpolate one 2D ICE image into the 3D volume requires $30ms$. Volume reconstruction time depends on the sweep angle and resolution. For instance, the total reconstruction time on GPU for a dense sweep of 40 images takes approximately $1.5s$. Data acquisition time is largely determined by the robotic system and the cardiac rate. Each $1°$ step is done in roughly $2s$, roughly twice the minimum possible due to heart rate (assuming a heart rate of 60 BPM). At each step the system must pause to acquire images across the cardiac cycle to build a 4D panorama. The total panorama creation time is 1-2 minutes, much less than the time for model building with clinical EP systems such as Ensite NavX [1] or CartoSound [2].

3.2 Instrument tracking results

In the instrument tracking experiment, the instrument was a $3mm$ diameter catheter with an EM sensor attached at the tip and calibrated to the catheter tip position. It closely resembled the dimensions and echogenic properties of an ablation catheter tool tip. The ICE catheter tracked the tool tip as it moved around the simulated PVO in the atrium phantom. Fig. 6(a) shows the experiment setup and Fig. 6(b) plots the imaging plane x-axis as it followed the tool tip. The lines show a top-view of imaging planes and the circles represent tool tip positions. Colors indicate corresponding imaging planes and tool tip positions. Fig. 6(c) is an example 2D ICE image during instrument tracking.

We also conducted an instrument tracking accuracy analysis study. Fig. 7(a) is a plot of the histogram of ICE imaging plane to tool tip distance. It shows that during majority of the trials, the tool tip is within $1 - 2mm$ from the imaging plane, thus it appears in the image. Fig. 7(b) is the histogram of ICE imaging plane pointing angular error. The average angular error is $0.3°$, and

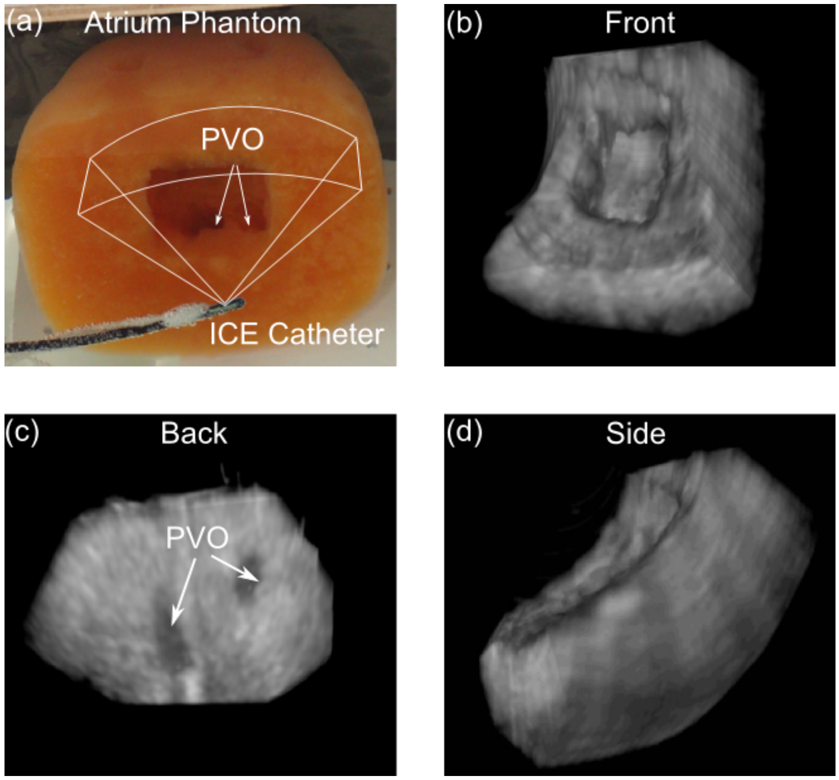

Fig. 5. Sweeping results. (a) Atrium phantom. (b)-(d) Mosaiced volume of the atrium phantom from three different views. The phantom PVO can be clearly seen from (c).

the maximum error is below 0.5°. When including the EM tracker angular error (0.5° RMS in angle [16]), the overall system angular tracking accuracy is 0.8°.

3.3 ICE Imaging Plane Thickness vs. System Accuracy

The inaccuracy of the EM trackers in ICE and the working instrument may result in the misalignment of the US imaging plane with the instrument. In this case the image may not show the tool tip. To analyze accuracy limits, the thickness of the ICE imaging plane can be compared to the possible positioning errors of the tool tip. Fig. 8 illustrates a simplified case considering only misalignment error in the sweep angle, using a typical ICE image plane depth $90mm$ and thickness $6mm$ [17].

RMS accuracy specifications for the EM tracker are $1.4mm$ in position and 0.5° in angle [16] and our system tracking accuracy is 0.3°. A simple geometric analysis of the worst-case accuracy scenario shows that an ablation catheter of diameter $3mm$ would be visible in the US image, although it may not be in the mid-plane. EM interference in clinical procedure rooms will likely decrease

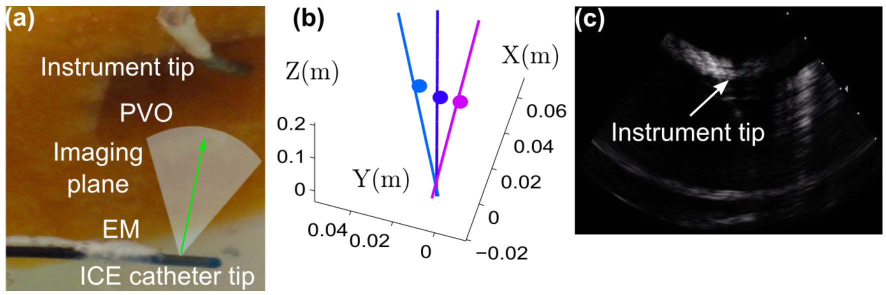

Fig. 6. Instrument tracking. (a) Instrument tip at simulated PVO. (b) Typical trajectory of imaging plane following the tool tip when looking top down from the imaging plane x-axis. The lines show imaging plane x-axis, the circles represent tool tip positions. Colors indicate corresponding imaging planes and tool tip positions. (c) Example 2D ICE image during instrument tracking.

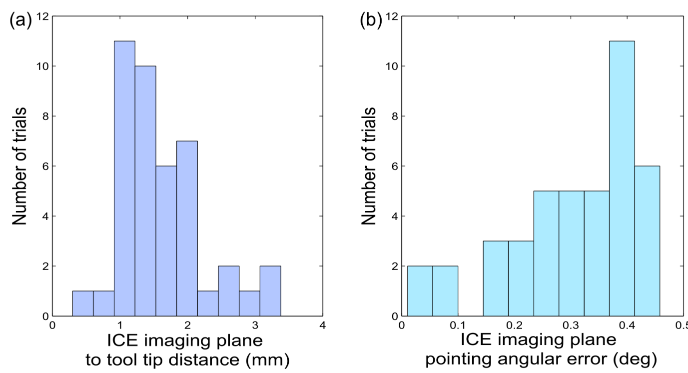

Fig. 7. Instrument tracking error analysis. (a) Histogram of ICE imaging plane to tool tip distance. During majority of the trials, the tool tip is within $1-2mm$ from the imaging plane, thus the tip appears in the image. (b) Histogram of ICE imaging plane pointing angular error. Average angular error is $0.3°$. The maximum error is below $0.5°$.

the accuracy of the EM trackers, although the close proximity of the imaging catheter to the ablation catheter will minimize the relative tracking errors.

4 Discussion and Conclusion

This is the first paper to demonstrate that robotic steering of an ICE catheter can produce high quality volumetric image and tracking is accurate enough to visualize moving instruments. The system manipulates floppy, deformable off-the-shelf ICE catheters, which are challenging to navigate manually. Our previous paper ([5]) detailed only the robot while this paper focuses on the imaging results, which have not been presented before.

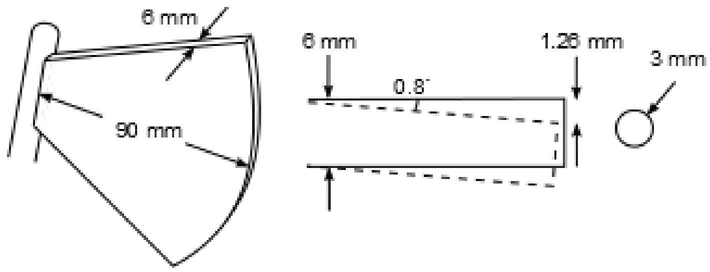

Fig. 8. Imaging plane thickness and tracking accuracy. (*Left*) Typical ICE imaging plane depth. (*Right*) cross section view of imaging plane for calculation of accuracy based on EM measurement accuracy of sweep angle: solid line is EM estimated boundary of image plane, dotted line is worst case scenario; circle is target ablation catheter cross section to show relative sizes.

Situational awareness plays a critical role in intra-operative procedure guidance. The current environment lacks real-time direct visual feedback of instrument-tissue interactions, which in part contributes to the low success rate of ablation procedures. The system presented in this paper addresses this issue with the following capabilities: (1) Build a real-time panorama of a ROI by spinning ICE at desired angles while keeping its tip at a fixed and safe location; (2) Instrument tracking and image-based tip location identification. Both tasks would be difficult to achieve manually. Our system can be easily extended to 4D (3D + time) based on our previous work on 4D US mosaicing and visualization with ECG gating [11, 12]. In addition to better spatial localization when compared to 2D views, the reconstructed 3D volume can also be used for surface and instrument segmentation, which would facilitate the integration with current clinical EM mapping systems or with an augmented virtual reality environment.

We believe our robotic system in combination with US image processing and visualization capabilities has the potential to further improve intra-operative procedure guidance.

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